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Anomalous Temporal Behavior of NP0532

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Recent high-precision studies of the temporal behavior of NP0532 in the radio[1] and optical[2] bands have yielded conflicting values of the second derivative of the period and, consequently, the physical processes with which the temporal behavior can be reconciled. It is the purpose of this communication to point out that a comparison of those two results with each other, and with other existing NP0532 data, yield the result that the average second derivative over periods of time larger than a few months is inconsistent with that measured in either of the high-precision measurements. One possible reconciliation of this difficulty may be obtained by invoking discontinuous increases in the period. We conclude that measured values of the second derivative may not necessarily give a reliable indication of the braking mechanism.

If the rate of change of the period P or the frequency ν is characterized by

$$\frac{dP}{dt} = \frac{K_P}{P^{n-2}} \quad \text{or} \quad \frac{d\nu}{dt} = -K_\nu \nu^n \tag{1}$$

where n = 5 for the gravitational radiation model,[3] and n = 3 for the magnetic dipole model,[3] and n = 1 for the relativistic solar wind model,[4] only the first and second derivatives of the known period or frequency are needed to specify n and, hence, the braking mechanism since (for constant K and n)

$$n = \frac{\nu\ddot{\nu}}{\dot{\nu}^2} = \frac{P\ddot{P}}{\dot{P}^2} + 2 \quad . \tag{2}$$

The high-precision measurements of P, $\dot{P}$ and $\ddot{P}$ are shown in Table 1, together with the deduced values of the parameter n. The

results of the Princeton[2] group were obtained from phase-locked optical measurements of NP0532 for a period of six weeks from March to May, 1969. They computed the first and second time derivative of the frequency by minimizing the residuals between the closest integer and the phase, defined as the first temporal moment of the second order Taylor expansion of the frequency. The results of the Arecibo[1] group were obtained by essentially the same method for the period November 1968 to August 1969.

The most obvious disparity in these two sets of data is in the measurement of the second derivative and, hence, in the braking index n. As shown in Table 1, the values of n are statistically inconsistent and imply different braking mechanisms. It is important to note that the time over which the Arecibo data was taken includes the time interval during which the Princeton measurement was made. However, because of the improved nature of the radio data since June 1969, the second derivative obtained by the Arecibo group may be considered as more representative of this later period. (We acknowledge Prof. F. Drake for this information.)

Because of the importance of understanding the true nature of this disparity, we have attempted to explore the degree of consistency between these and other NP0532 data extant in the literature. Since all of the data include measurements of P, we can use either the Princeton or Arecibo values for the period, Po, and its first derivative, $\dot{P}o$, to obtain the value of P at earlier or later times as a function of the braking index n.

From Equation (1) we get

$$P = Po\left[1 + \frac{\dot{P}o}{Po}(n-1)\,\Delta t\right]^{\frac{1}{n-1}} \qquad n \neq 1$$

$$= P_o \exp\left[\frac{\dot{P}o}{Po}\Delta t\right] \qquad n = 1 \tag{3}$$

Values of P predicted from these two standards are presented in Table 2, compared with the actually measured values as a function of n. Of the existing additional data, only the X-ray measurement of the Rice group in 1967[5,6] yields statistically significant information because of the long temporal lever arm available. As can be seen, for values of n appropriate for the gravitational radiation model (n = 5) or the magnetic dipole model (n = 3), the measured period on June 4, 1967 is longer than that which would be obtained by extrapolating either the radio or the optical measurement. Furthermore, the period measured on March 17, 1969 is also longer than that obtained from the extrapolation of the June 28 measurements for these same values of n. Thus, when extrapolating backward in time, the individually deduced n's are all smaller than the locally measured values given in Table 1. Extrapolating forward in time, we see that for both the gravitational and magnetic dipole models, the measured period on June 28 is shorter than the extrapolated period based on the measurements on March 17. In this case the best fitting value of n is about 8 to 9, a much larger slowing-down rate than predicted by any of the simple models.

Alternatively, we can perform the same sort of analysis in a manner which is independent of the simple braking theory discussed above. We

define an average second derivative, $\langle\ddot{P}\rangle$, by assuming that we can use the Taylor expansion to arbitrary order and then combine all the terms of order higher than the first into an average second order term:

$$P = Po + \dot{P}o\,\Delta t + \tfrac{1}{2}\,\langle\ddot{P}\rangle\,(\Delta t)^2 \tag{4}$$

Solving for $\langle\ddot{P}\rangle$;

$$\langle\ddot{P}\rangle = \frac{2}{\Delta t}\left[\langle\dot{P}\rangle - \dot{P}o\right] \tag{5}$$

where

$$\langle\dot{P}\rangle = \frac{P - Po}{\Delta t} \tag{6}$$

If the period is a smoothly varying function of time, which can be well represented by second order Taylor expansion, the long-term average second derivatives must be consistent with the locally measured values. As can be seen from Table 3 , however, the average second derivatives are totally inconsistent with the conclusions reached by either the Princeton or the Arecibo groups. In fact, the previously published Arecibo data[7] yield the same sort of qualitative inconsistency; the weighted average of all the average second derivatives deduced in this manner from the previously published Arecibo periods from November 1968 to February 1969 and the Arecibo Po and $\dot{P}$o for June 28.0 is +0.1 ± 0.1, in contrast to the value of -0.024 ± 0.006 reported on the basis of time of arrival analysis.[1]

In short, extrapolating backward in time on the basis of a locally measured period and its first derivative seems to yield

shorter periods than those actually measured (implying that the average second derivative must be positive, i.e. $n < 2$). On the other hand, extrapolating forward in time yields longer periods (implying negative second derivatives which are larger than those measured locally, i.e. $n > 5$).

We suggest the following semi-empirical argument to account for the qualitative behavior of the apparent discontinuities. Let us assume that there are finite discontinuities, superposed on an otherwise smooth braking mechanism, which result (presumably) from the sudden speedup of the rotating neutron star. Then, a locally measured second derivative is more likely to be consistent with the smooth braking mechanism, whereas the average second derivative over a long period of time will be greater (or smaller) than that measured locally for an extrapolation made backward (or forward) in time. A finite discontinuity resulting in a speedup of about 196 ns over a period of less than 1 week was observed[8,9] for the Vela pulsar, PSR 0833-45. The average speedup required to account for the inconsistencies in the second derivative of NP0532 is only 1 to 2 ns per 100 days. It is conceivable, therefore, that there may exist a whole spectrum of discontinuities of which the observed speedup of the Vela pulsar is but one example. Clearly, further continuous observations of both the Crab and Vela objects (as well as other pulsars) are required to further substantiate this point of view.

If it were possible to make instantaneous measurements of the second derivative, the hypothesis of truly discontinuous speedups could be tested since each local value of $\ddot{P}$ would be consistent with

the prevalent braking mechanism even though the average value over longer periods of time would not. The obvious extension of this argument is that the measurement which is made over the smallest interval of time should be the most representative of the smooth braking mechanism. If the speedups are not truly discontinuous, however, but have recovery times which are finite (and which may even exceed the average time between successive speedups), the ability to distinguish between the prevalent braking mechanisms on the basis of local measurements of $\ddot{P}$ becomes extremely difficult.

On the assumption of truly discontinuous speedups, the evidence would seem to favor gravitational radiation as the dominant energy loss process in NP0532, since the Princeton measurement is taken over a shorter time base than is that of the Arecibo group (the fact that it has a larger negative value is also consistent with what would be expected from a measurement which is closer to being instantaneous). Gravitational braking, however, presents severe difficulties in achieving consistency with the known age of the Crab Nebula.[3] The more reasonable (perhaps) assumption of finite "discontinuities" would indicate that none of the existing models for the prevalent braking mechanisms are preferentially supported by the data.

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Table 1.

Measured Periods, First and Second Derivatives, and the Corresponding Values of the Braking Index n

Date	Julian Date	P (ns)	P (ns/d)	P (ps/d^2)	n
1969, June 28[1]	2440400.5	33099324.09±.05	36.518 ±.002	-.024 ±.006	2.64 ±.62
1969, March 17[2]	2440297.50904	33095563.9268 ±.0037	36.52256± .00050	-.1107± .0260	4.76 ±.65

Table 2.

Extrapolated Periods (ns)

n	1969, June 28 $\downarrow$ 1967, June 4	1969, June 28 $\downarrow$ 1969, March 17	1969, March 17 $\downarrow$ 1967, June 4	1969, June 28 $\uparrow$ 1969, March 17
-3		33095564.13		
-2		33095563.92		
-1		33095563.71		
0	33071797.72	33095563.49	33071789.79	
1	33071786.27	33095563.28 ±.21	33071781.25	
2	33071774.81	33095563.07	33071772.70	
3	33071763.34 ± 1.5	33095562.85	33071764.14 ±.32	33099325.21
4	33071751.85	33095562.64	33071755.57	33099325.00
5	33071740.35	33095562.43	33071747.00	33099324.79
6				33099324.57 ±.05
7				33099324.36
8				33099324.14
9				33099323.93
measured	33071784 ±6	33095563.9268 ±.0037	33071784 ±6	33099324.09 ±.05

Table 3.

Average First and Second Derivatives

		$\langle \dot{P} \rangle$ (ns/d)	$\langle \ddot{P} \rangle$ (ps/d^2)
1969, June 28 →	1969, March 17	$36.510 \pm .0005$	$0.155 \pm .04$
	1967, June 4	$36.506 \pm .008$	$0.0318 \pm .022$
1969, March 17 →	1969, June 28	$36.510 \pm .0005$	$-0.244 \pm .014$
	1967, June 4	$36.505 \pm .009$	$0.503 \pm .028$